The GRB/XRF-SN Association

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ABSTRACT

There is mounting evidence that long duration gamma ray bursts (GRBs) and X-ray flashes (XRFs) are produced by highly relativistic and narrowly collimated jets ejected in core collapse supernova (SN) explosions akin to SN 1998bw. We review the history of the GRB-SN association idea and its observational verification. We summarize the present evidence for a GRB/XRF-SN association. We comment on the possibility that most, perhaps all, SN explosions produce GRBs, including SNe of Type Ia which may produce short GRBs/XRFs. We list the major open questions that follow from a GRB/XRF-SN association. Possible uses of the GRB-SN association in cosmology are pointed out.

Subject headings: gamma rays: bursts

1. History of the GRB/XRF-SN association

The history of scientific breakthroughs is as fascinating as the breakthroughs themselves. The history of the GRB/XRF-SN association is not an exception.

The production of gamma rays in supernova (SN) explosions was suspected (Colgate 1959 unpublished) long before the discovery of gamma ray bursts (GRBs) in 1967 by the Vela satellites. Klebesadel, Strong & Olson (1973), in their discovery paper, reported on a catalog search of SNe coincident in time and sky position with the first 13 detected GRBs. Colgate's suggestion (1968, 1974) that the breakout of the shock wave from the stellar surface in core-collapse SNe may produce GRBs could be true, if GRBs were observable only from relatively small cosmological distances. This is because there are more than 10^6 SN explosions per day in the observable universe and only 2-3 GRBs per day. However, the Solar Maximum Mission Satellite (SMM) did not detect a prompt GRB from the nearest SN explosion in recent times, SN 1987A in the Large Magellanic Cloud, which happened to be in its field of view (Chupp et al. 1987). Dar & Dado (1987) considered the possibility that radiative decay of neutrinos

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from core-collapse SN explosions would produce GRBs and used the disparity between the cosmic SN and GRB rates, as well as SN 1987A, to derive bounds on ν radiative decay. Goodman, Dar & Nussinov, who studied the production of e^+e^- pairs by $\nu\bar{\nu}$ annihilation above the neutrino sphere in core collapse supernova explosions, estimated that neutrino annihilation in accretion induced collapse of neutron stars (ns), or in ns-ns mergers in close binaries due to gravitational wave emission, could form relativistic fireballs (Paczynski 1986; Goodman 1986) that produce cosmological GRBs[1]. Yet, the authors pointed out that baryon contamination of the fireball (now known as "baryon-load") poses a severe problem for this mechanism.

The first strong indication that GRBs are indeed cosmological in origin came from their isotropic sky distribution and their peak intensity distribution measured by BATSE on board the Compton Gamma Ray Burst Observatory (CGRO) shortly after its launch (Meegan et al. 1992). Following these observations, cosmological fireballs produced by neutrino annihilation in ns-ns mergers became the leading candidate for the origin of cosmological GRBs (see, e.g., Fishman & Meegan 1995 and references therein). Dar et al. (1992), however, suggested that neutrino-annihilation around "compact supernova" produces cosmological GRBs, but Woosley (1993a,b) argued that cosmological GRBs *cannot* be produced in SN explosions, and proposed instead that they are produced by mildly relativistic jets ejected in the direct collapse of massive stars into black holes *without* an associated supernova, which he dubbed *failed supernovae* or *collapsars* [2]. Finally, Shaviv and Dar (1995) suggested that highly relativistic jets ejected in core collapse supernovae, or in supernova explosions driven by accretion/merger induced collapse of compact stars in close binaries, can produce the cosmological GRBs by inverse Compton scattering of circumburst light. This idea was later incorporated into the cannonball (CB) model of GRBs (Dar & De Rújula 2000; 2003).

The approximate localization of GRBs by the Beppo-SAX satellite (Costa et al. 1997) led to discovery that long duration GRBs have afterglows (AGs), i.e., long term emission of radiation at longer wavelengths[3] (X-Rays: Costa et al. 1997; Optical band: Van Paradijs et al. 1997; Radio band: Kulkarni et al. 1998). These afterglows led to the precise sky localization of GRBs, the discovery of their host galaxies and the measurements of their redshifts. Long GRBs were found to be located in star formation regions of normal star

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[1]The idea that neutrino annihilation in ns-ns mergers produces cosmological GRBs was reproduced later by Eichler et al. 1989.

[2]This GRB-SN *dissociation* has been referenced in many recent articles as the original suggestion of ... a GRB-SN *association*.

[3]Detection of a γ-ray emission at GeV and sub-GeV energies with EGRET on board CGRO, during the burst and up to ~ 2h after it, has been reported before by Hurley (1994).

forming galaxies at large cosmological distances. The approximate power-law decline with time of their afterglows has been used to conclude (e.g., Wijers et al. 1997; Piran 1999) that GRBs are produced in relativistic fireballs and their afterglows are synchrotron radiation from shock accelerated electrons in the collision of the fireball (or its accelerated ejecta) with the interstellar medium (Paczynski & Rhoads 1993; Katz 1994a,b; Meszaros & Rees 1997). Arguments that the observational data actually indicate that GRBs and their afterglows are produced by narrow relativistic jets similar to those observed in quasars and microquasars (Dar 1997; 1998) rather than by relativistic fireballs were initially ignored or dismissed by the majority of the GRB community.

The localization of long duration GRBs in star formation regions, which more than 90% of the SNe take place, and not in the galactic halos where most binary neutron stars are expected to reach long before they merge by gravitational wave emission, was the first observational indication that long duration GRBs may be produced by the death of massive stars in SN explosions. The first direct evidence for an SN-GRB association came a little later from the discovery by Galama et al. (1998) of the very bright SN 1998bw, at redshift $z = 0.0085$, within the Beppo-SAX error circle around the measured position of GRB 980425 (Soffita et al. 1998; Pian et al. 1999). Its light curve indicated that the time of the SN explosion was within -2 to $+0.7$ days of the GRB (Galama et al. 1998, Iwamoto et al. 1998). This evidence did not fit at all into the framework of the fireball model (FB) of GRBs. The total equivalent isotropic γ-ray energy release, $\sim 8\times10^{47}$ erg, was some 5 orders of magnitude smaller than that expected from a "classical" GRB at $z = 0.0085$. The ruling majority concluded that either SN 1998bw and GRB 980425 were not physically connected or that, if they were, they represent a new subclass of rare events (e.g. Bloom et al. 1998; Woosley, Eastman & Schmidt 1999; Hurley et al. 2002; Galama 2003). These would be associated with what Paczynski (1998a) and Iwamoto et al. (1998) called "hypernovae": super-energetic explosions with kinetic energy exceeding 10^{52} erg, as was inferred for SN 1998bw from its high expansion velocity and luminosity (Patat et al. 2001), and from the very strong radio emission from its direction (Kulkarni et al. 1998).

Yet, a physical association between GRB 980425 and SN 1998bw was consistent with GRB 980425 being a normal GRB produced by a highly relativistic jet ejected in SN explosion and viewed off axis ((Shaviv & Dar 1995; Wang & Wheeler 1998) at a viewing angle which is a few times larger than the typical viewing angle of ordinary GRBs. Likewise, core collapse SN can be highly asymmetric and SN 1998bw could appear to be an unusually bright SN, perhaps because it was viewed near axis (Hoeflich, Wheeler & Wang 1999). These possibilities were first ignored by the majority of the GRB and SN communities, which were accustomed to spherical models of SN explosions and GRB "fireballs".

SN 1998bw was initially classified as Type Ib (Sadler et al. 1998) and later as a peculiar Type Ic (Filippenko 1998; Patat and Piemonte 1998, Patat et al. 2001). Its discovery initiated intensive searches of positional and approximate temporal coincidences between GRBs and SN explosions (e.g. Kippen et al. 1998), in particular Type Ib and Ic SNe (Woosley, Eastman & Schmidt 1999). The search yielded two inconclusive associations, one of them, between the peculiar Type II SN 1997cy, at $z = 0.063$, and the short-duration (~ 0.2 s) GRB 970514 (Germany et al. 2000) and another one between the Type Ic SN 1999E at $z = 0.0261$ and the long-duration GRB 980910 (Thorsett & Hogg 1999; Rigon et al. 2003). Nevertheless, Dar & Plaga(1999) [4]) and Dar & De Rújula (1999) advocated the view that most core-collapse SN explosions result in GRBs.

Core collapse SNe are far from being standard candles. In particular SNe of type Ib/Ic have light curves, peak intensity and peak time which display a large dispersion. But if they are axially as opposed to spherically symmetric —as they would be if a fair fraction of them emitted bipolar jets— much of their diversity could be due to the angle from which we see them. Exploiting this possibility to its extreme, i.e. using SN 1998bw as an ansatz standard candle, Dar (1999a) suggested at the '1'st Rome Intl. Workshop on GRBs in the Afterglow Era' that the AGs of all GRBs may contain a contribution from an SN akin to SN 1998bw, placed at the GRB's position. However, before GRB 980425 only the redshift of GRB 971214 (z=3.42) and that of GRB 970508 (z=0.835) were known. An SN 1998bw displaced to z=3.42 was too faint to be observed, while the data on the late-time optical AG of GRB 970508 after subtraction of the contribution from the host galaxy was not accurate enough to allow a conclusive test of the GRB-SN association.

The first claim of a possible detection of an SN light in the afterglow of a GRB was made by Bloom et al. (1999) who interpreted a faint red light "bump" superimposed on the late-time afterglow of GRB 980326 as that due to an SN akin to SN 1998bw. However, the unknown redshift of GRB 980326 and the sparse data on its late-time afterglow did not allow a definite conclusion. Shortly after publishing their paper on the possible evidence of an SN light in the AG of GRB 980326, four leading authors of this paper reported on behalf of the Caltech-CARA-NRAO GRB Collaboration the measurement of the redshift of GRB 970228 (Djorgovski, Kulkarni, Bloom & Frail 1999), but, surprisingly, they did not proceed to examine whether the late-time "bump" in the optical light curve of the AG of GRB 970228 is due to an SN akin to SN 1998bw. This was examined by Dar (1999b) as soon as the redshift of GRB 970228 became known, who reported that the addition of the light of "a standard candle SN 1998bw at the GRB redshift, z=0.695, explains better

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[4]That paper was submitted to Nature in summer 1998

the behavior of the optical afterglow of GRB 970228 than an extrapolated power-law alone and is consistent with the measured afterglows of all other GRBs". This was immediately confirmed for GRB 970228 by Reichart (1999) and later by Galama et al. (1999). Not only the magnitude and the peak time of the 'bump' were correctly predicted, but also its broad band spectrum and its evolution coincided with those of SN 1998bw displaced to the GRB position.

These findings prompted a search for supernova bumps in the afterglow of other, relatively nearby GRBs (in GRBs with $z > 1.2$, the light of a standard candle SN 1998bw displaced to the GRB position becomes too faint in the visible bands, in particular, if it suffers also a considerable extinction by dust in the host and/or Milky Way). However, the AGs of GRB 990712, GRB 980613 and GRB 980703 did not show clear SN bumps (e.g., Hjorth et al. 1999, Sahu et al. 1999; Holland et al. 2000). But, lack of evidence for an underlying SN is not evidence against the presence of a SN. SNe produce visible bumps in the optical afterglows of nearby GRBs only if the host galaxy and the jet are not too bright relative to the SN whose light may also suffer a considerable extinction in the host. Moreover, in many cases lack of high quality observations at late time, lack of a reliable estimate of the late-time AG from its early time behaviour (when the contributions of the SN and the host galaxy are negligible) and lack of a reliable method for estimating the extinction of the SN in the host galaxy, prevented the discovery of an underlying SN. The last two deficiencies were eliminated once the cannonball (CB) model of GRBs (Dar & De Rújula 2000; 2003) was demonstrated to provide a good, simple and universal description of the AGs of all the GRBs of known redshift (Dado et al. 2002a; 2003a). In the CB model GRBs are produced by highly relativistic jets of plasmoids (cannonballs) of ordinary matter ejected in SN explosions akin to SN 1998bw. In the CB model analysis of these AGs, significant evidence or clear hints were found for a GRB-SN association in all the cases in which the SN could be observed in practice (about 1/2 of the total) and was not found when it could not be seen. This led Dado, Dar & de Rújula (2002a) to conclude that perhaps all long duration GRBs are produced in SN explosions akin to SN 1998bw (Dar & Plaga 1999; Dar & De Rújula 2000; Dado et al. 2002a). Despite the mounting evidence for a GRB-SN association (GRB 990712: Bjornsson et al. 2001; Dado et al. 2002a, GRB 980703: Holland et al. 2001; Dado et al. 2002a, GRB 000418: Dar & De Rújula 2000a; Dado, Dar & De Rújula 2000a, GRB 991208: Castro-Tirado et al. 2001; Dado, Dar & De Rújula 2002a, GRB 970508: Sokolov 2001; Dado et al. 2002a, GRB 000911:Lazzati et al. 2001; Dado et al. 2002 unpublished), GRB 010921: Dado, Dar & De Rújula 2002d) the majority of the GRB community remained skeptical and continued to argue that the GRB-SN association is true only for a rare type of GRB and not for the classical long GRBs as a a whole (see e.g. Hurley, Sari, & Djorgovski 2003, Galama 2003, Waxman 2003).

Scientific theories must be falsifiable. Thus, in order to test/demonstrate the validity of the CB model and its underlying GRB-SN association, in four cases of relatively nearby GRBs, Dado, Dar & De Rújula used the CB model fit to the early-time AG to *predict* the late-time AGs where an SN contribution should become observable. In all four cases, GRB 011121 (Dado et al. 2002b), GRB 020405 (Dado et al. 2002c), GRB 0212111 (Dado et al. 2003b) and GRB 030329 (Dado et al. 2003c), we have successfully *predicted* the discovery of an SN akin to SN 1998bw and what its contribution would be in the different optical bands. In particular, in the case of GRB 030329 we foretold the day (April 8, 2003) that the underlying SN would be discovered *spectroscopically* (Dado et al. 2003c). In all these cases of relatively nearby GRBs, we urged the observers to do the obvious: to try to verify spectroscopically the existence of an underlying SN and its type. Indeed, it was the dramatic spectroscopic discovery on April 8, 2003 of SN 2003dh, in the very bright afterglow of the relatively nearby GRB 030329 (Garnavich et al. 2003; Staneck et al. 2003; Hjorth et al. 2003) which finally convinced many of the GRB and SN communities that long GRBs are produced in SN explosions akin to SN 1998bw.

In the CB model bursts such as GRB 980425 and XRFs are GRBs viewed further off axis (Dar & De Rújula 2000, 2003; Dado, Dar & De Rújula 20003d. Their larger viewing angles result in a much smaller fluence or photon number-count. Consequently, only relatively close by XRFs (i.e. XRFs with relatively small z) are detected with the current sensitivities of the X-ray satellites. Thus the optical AG of most XRFs should contain a detectable light from an SN akin to SN 1998bw at the XRF's position which peaks around 15- 20 days after the XRF. Indeed the optical afterglow of all well localized XRFs show evidence for an SN peaking around that time (GRB 980425: Galama et al. 1998; XRF 020903: Soderberg et al 2002; XRF 030723: Fynbo et al. 2003, 2004; Tominaga et al. 2004; XRF 031203: Bersier et al. 2004; Tagliaferri et al. 2004; Thomsen et al. 2004; Gal-Yam et al. 2004).

2. The Current Evidence For the GRB/XRF-SN Association

2.1. Indirect Evidence

More than 90% of core collapse SNe take place in star formation regions. If long duration GRBs are produced in SN explosions, then GRBs are expected to be located mainly in star formation regions. Indeed:

- The well localized GRBs were found to be located in star formation region in distant galaxies (e.g. Paczynski, 1998b; Holland & Hjorth 1999).

- The blue colours and/or precise spectroscopy of the host galaxies of GRBs indicate that they are mainly star forming galaxies. (Djorgovsky et al. 2001; Bloom, Kulkarni & Djorgovski 2002).

- The optical afterglows of GRBs indicate that the GRBs environment is that expected from SN explosions in star formation regions (Dado, Dar & De Rújula 2003c, 2004).

Finally, the remarkable success of the CB model, which is based on the GRB/XRF-SN association, in providing a good, simple and universal description of GRBs and XRFs (Dar & De Rújula 2003; Dado et al. 2003f and references therein) and of their afterglows (Dado et al. 2002a,b,c; 2003a,b,c,d; 2004 and references therein) has been strong evidence for the GRB/XRF-SN association.

2.2. CB model evidence from the prompt γ-ray emission

The CB model is illustrated in Fig.(1). In the CB model, long-duration GRBs are produced in the explosions of ordinary core-collapse SNe. Following the collapse of the stellar core into a neutron star or a black hole, and given the characteristically large specific angular momentum of stars, it is hypothesized that an accretion disk or torus is produced around the newly formed compact object, either by stellar material originally close to the surface of the imploding core and left behind by the explosion-generating outgoing shock, or by more distant stellar matter falling back after its passage (De Rújula 1987). A highly relativistic CB is emitted along the rotation axis, as observed in microquasars, when part of the accretion disk falls abruptly onto the compact object (e.g. Mirabel & Rodrigez 1999; Rodriguez & Mirabel 1999 and references therein). Such CBs encounter relatively small baryonic column densities because lack of rotational support along the rotation axis results in fast accretion of matter along the polar directions. The bipolar ejection of relativistic CBs may have been detected in SN 1987A as shown in Fig. (2) borrowed from Nisenson & Papaliolios 2000).

The high-energy photons of a single pulse in a GRB/XRF are produced as a CB coasts through the ‘glory’ surrounding the parent SN. The glory is the “echo” (or *ambient*) light from the SN, permeating the “wind-fed” circumburst density profile, previously ionized by the early extreme UV flash accompanying an SN explosion, or by the enhanced UV emission that precedes it.

The CBs of the CB model are inspired by the ones observed in quasar and microquasar emissions. One example of the latter is shown in the upper panel of Fig. (3), showing

two opposite CBs emitted by the microquasar XTE J1550-564 (Kaaret et al. 2003). The winds and echoes of GRB-generating SNe are akin to those emitted and illuminated by some very massive stars. The light echo (or glory) of the stellar outburst of the red supergiant V3838 Monocerosis in early January 2002 is shown in the lower panel of Fig. (3), from Bond et al. (2003). In a sense all the CB model results for the prompt gamma-ray emission follow from superimposing the two halves of Fig. (3) and working out in detail what the consequences —based exclusively on Compton scattering— are.

The electrons enclosed in the CB Compton up-scatter photons to energies that, close to the CBs direction of motion, correspond to the γ-rays of a GRB and less close to it, to the X-rays of an XRF. Each pulse of a GRB or an XRF corresponds to one CB. The timing sequence of emission of the successive individual pulses (or CBs) reflects the chaotic accretion process and its properties are not predictable, but those of the single pulses are (Dar & De Rújula 2003 and references therein). In particular, the major observed properties of GRB pulses are *correctly predicted/reproduced* (Dar & De Rujula 2003). They include:

- The characteristic energy $E = \mathcal{O}(250)$ keV of the γ rays (Preece et al. 2000; Amati et al. 2002).

- The narrow distribution of the "peak" energies of the GRB spectra (e.g. Preece et al. 2000).

- The duration of the single pulses of GRBs: a median $\Delta t \sim 1/2$ s full width at half-maximum (McBreen et al. 2002).

- The characteristic (spherical equivalent) number of photons per pulse, $N_\gamma \sim 10^{59}$on average, which, combined with the characteristic γ energy, yields the average total (spherical equivalent) fluence of a GRB pulse: $\sim 10^{53}$ erg.

- The general *FRED* pulse-shape: a very "fast rise" followed by a fast decay $N(t) \propto 1/t^2$, inaccurately called "exponential decay" (Nemiroff et al. 1993, 1994; Link & Epstein 1996; McBreen et al. 2002).

- The γ-ray energy distribution, $dN/dE \sim E^{-\alpha}$, with, on average, $\alpha \sim 1$ exponentially evolving into $\alpha \sim 2.1$ and generally well fitted by the "Band function" (Band et al. 1993).

- The time–energy correlation of the pulses: the pulse duration decreases like $\sim E^{-0.4}$ and peaks earlier the higher the energy interval (e.g. Fenimore et al. 1995; Norris et al. 1996; Ramirez-Ruiz & Fenimore 2000; Wu & Fenimore 2000); the spectrum gets softer as time elapses during a pulse (Golenetskii et al. 1983; Bhat et al. 1994).

- Large polarizations of the prompt γ rays from GRBs (Coburn & Boggs 2003) and a much smaller polarization in XRFs.

- Various correlations between pairs of the following observables: photon fluence, energy fluence, peak intensity and luminosity, photon energy at peak intensity or luminosity, and pulse duration (e.g. Mallozzi et al. 1995; Liang & Kargatis 1996; Crider et al. 1999; Lloyd, Petrosian & Mallozzi 2000; Ramirez-Ruiz & Fenimore 2000; McBreen et al. 2002; Kocevski et al. 2003).

2.3. Direct Evidence in Optical AGs of Nearby GRBs/XRFs

If GRBs/XRFs are produced by relativistic jets which are ejected in core collapse SN explosions then their AGs consist of three contributions, from the relativistic jet [RJ], the concomitant SN, and the host galaxy [HG] :

$$F_{AG} = F_{RJ} + F_{SN} + F_{HG}\,, \tag{1}$$

the latter contribution being usually determined by late-time observations, when the RJ and SN contributions become negligible.

Shortly after an SN explosion, the SN brightness increases as a result of fast expansion of its photosphere. Dissipation of the shock energy and decay of the main radioisotopes, ^{56}Ni and ^{56}Co in the ejecta which power the light emission, reverse this increase and the brightness decays almost exponentially. In the case of SN 1998bw the peak brightness was reached around $t \approx (1+z) \times 15$ days (see e.g., Galama et al. 1998). Thus, the contribution of an SN akin to SN 1998bw displaced to the GRB redshift, is expected to peak around $t \approx (1+z) \times 15$ days.

The colour lightcurves (Galama et al. 1998; McKenzie & Schaefer 1999; Sollerman et al. 2000; Fynbo et al. 2000; Sollerman et al. 2002) and spectroscopic evolution of SN 1998bw (Iwamoto et al. 1998; Patat et al. 2001; Stathakis et al. 2000) were followed in great detail during the first two years after explosion. They can be used to estimate the SN contribution, using SN 1998bw as an ansatz standard candle (Dar 1999b). With this approximation, the spectral energy density of the optical AGs of GRBs with known redshift z can be written as (Dar & De Rújula 2000; Dado et al. 2002a),

$$F_{SN}[\nu, t] = \frac{1+z}{1+z_{bw}}\,\frac{D_L^2(z_{bw})}{D_L^2(z)}\,F_{bw}[\nu', t']\,A_{SN}(\nu, z, t)\,, \tag{2}$$

where $A_{SN}(\nu, z, t)$ is the attenuation along the line of sight to the SN. $\nu' = [(1{+}z)/(1{+}z_{bw})]\,\nu$, $t' = [(1+z_{bw})/(1+z)]\,\nu$ and $D_L(z)$ is the luminosity distance (we have used a cosmology

with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 65$ km/s/Mpc) which may depend on time because of sublimation of dust in the host galaxy along the line of sight by the GRB and AG.

The SN contribution can be resolved from the optical AG of a GRB and compared with the 'SN 1998bw standard candle' ansatz only if the total AG and the individual contributions from both the host galaxy and the jet are known accurately enough. Two main procedures have been employed for calculating $F_{RJ}[\nu, t]$ at late times. The first procedure, employed mainly by the observers, used an ad hoc parametrization (a broken power-law) to extrapolate the early time RJ contribution to late times. Lacking a theoretical basis[5], this procedure is unreliable, in particular in cases such as GRB 030329 where the AG does not have a simple broken power-law behaviour. Moreover, this procedure requires knowledge of the 'break time', but a few attempts to predict these break times from the total GRB fluence and the observed early time behaviour have failed completely.

The second procedure used the CB model fit of the early time afterglow in order to calculate $F_{RJ}[\nu, t]$ at late time. In this model the relativistic jet is made of plasmoids (cannonballs) of radius R with a bulk motion Lorentz factor $\gamma(t)$ moving at an angle θ relative to the line of sight. Their Doppler factor δ, for the relevant Lorentz factors and viewing angles, $\gamma^2 \gg 1$ and $\theta^2 \ll 1$, is given to an excellent approximation, by

$$\delta = \frac{1}{\gamma\,(1-\beta\,\cos\theta)} \approx \frac{2\gamma}{1+\gamma^2\,\theta^2}\ , \tag{3}$$

The deceleration of the CBs in the ISM, i.e. $\gamma(t)$, is determined by energy-momentum conservation (Dado et al. 2002a). The AG of a CB is mainly due to synchrotron radiation from accelerated electrons in the CB's chaotic magnetic field. It has the approximate form (Dado et al. 2003e):

$$F_{RJ}[\nu, t] \propto n^{(1+\hat\alpha)/2}\, R^2\, \gamma^{3\hat\alpha-1}\, \delta^{3+\hat\alpha}\, A(\nu, t)\, \nu^{-\hat\alpha}\,, \tag{4}$$

with $\hat\alpha$ changing from ~ 0.5 to ~ 1.1 as the emitted frequency crosses the *"injection bend"*,

$$\nu_b(t) \simeq \nu_0\, \left[\frac{[\gamma(t)]^3\,\delta(t)}{10^{12}}\right]\, \left[\frac{n_p}{10^{-3}\ cm^3}\right]^{1/2}\ , \tag{5}$$

where we estimated (Dado et al. 2003) that $\nu_0 \sim 1.87 \times 10^{15}$ Hz and n_p is the baryon density of the interstellar medium. The attenuation $A(\nu, t)$ is a product of the attenuation in the host galaxy, in the intergalactic medium, and in our Galaxy. The attenuation in our galaxy

[5]A broken power-law has been frequently used to fit optical AGs of GRBs but was never derived theoretically.

in the direction of the GRB or XRF is usually estimated from the Galactic maps of selective extinction, $E(B-V)$, of Schlegel, Finkbeiner & Davis (1998), using the extinction functions of Cardelli et al. (1989). The extinction in the host galaxy and the intergalactic medium, $\mathrm{A}(\nu, \mathrm{t})$ in Eq. (2), can be estimated from the difference between the observed spectral index *at very early time when the CBs are still near the SN* and that expected in the absence of extinction. Indeed, the CB model predicts —and the data confirm with precision— the gradual evolution of the effective optical spectral index towards the constant value ≈ -1.1 observed in all "late" AGs (Dado et al. 2002a, 2003a). The "late" index is independent of the attenuation in the host galaxy, because after a couple of observer days after the explosion, the CBs are typically already moving in the low-column-density, optically-transparent halo of the host galaxy.

Using the CB model, Dado et al. (2002a,b,c, 2003a,b,c,d,e, 2004) have shown that the optical AG of *all* relatively nearby GRB with known redshift (all GRB with z < 1.2) contains evidence or clear hints for an SN 1998bw-like contribution to their optical AG, suggesting that most —and perhaps all— of the long duration GRBs are associated with 1998bw-like supernovae (in the more distant GRBs, the ansatz standard candle could not be seen, and it was not seen). This evidence is summarized in Table I. The light curves or spectra of AGs which show clear photometric and/or spectroscopic evidence for an SN contribution akin to SN 1998bw are also displayed in Figs. 3-8. Cases where scarcity of data, lack of spectral information and multicolour photometry, and uncertain extinction in the host galaxy prevented a firm conclusion are listed in the table with a question mark. Similar conclusions were reached recently by Zeh, Klose & Hartmann (2003) using a phenomenological analysis of the late-time AGs of GRBs.

For CBs of constant radius moving in a constant density ISM, energy-momentum yields, $\gamma(t) \sim \delta(t) \sim t^{-3}$, and then it follows from Eq. (4) that at late time the RJ contribution decreases like $F_{RJ} \sim t^{-2.13}\, \nu^{-1.1}$ (Dado et al. 2002a;2003a). For $n_p \sim 1/r^2$, energy-momentum conservation implies that at late time, $\delta(t) \sim 2\,\gamma(t)$ approach a "constant" value and then Eq. (4) yields $F_{RJ} \sim t^{-2.10}\, \nu^{-1.1}$, which has practically the same asymptotic behaviour Thus, in cases where early time AG data is not available, we recommend the use of this approximate form with a normalization fitted directly to the data for subtraction the RJ contribution to the late-time AG.

2.4. GRB 980425/SN 1998bw and the GRB/XRF-SN association

In the CB model, XRFs are GRBs viewed further off axis (Dar & de Rújula 2003, Dado, Dar & De Rujula 2003f). Their properties are similar to those of GRB 980425, which, in the

CB model, was interpreted (Dar & De Rújula 2000, 2003; Dado et al. 2002a, 2003a) as an entirely normal GRB produced by the explosion of SN 1998bw. Its jet of CBs was ejected at an angle $\theta \sim 3.9/\gamma \sim 8$ mrad, a large value which, combined with the progenitor's unusually small redshift ($z = 0.0085$) conspired to produce a rather typical GRB fluence (Dar & De Rújula 2000, 2003; Dado et al. 2002a, 2003a). GRB 980425 is by definition a GRB and not an XRF, as the central value of its peak energy, $E_p = 54.6 \pm 20.9$ keV (Yamazaki, Yonetoku & Nakamura 2003), is just above the "official" borderline 40 keV for XRFs. In the CB model, SN 1998bw, associated with GRB 980425, is an ordinary core-collapse SN: its "peculiar" X-ray and radio emissions were not emitted by the SN, but were part of the GRB's AG (Dado et al. 2002a, 2003a). The high velocity of its ejecta is attributed to the SN being viewed almost "on axis".

The larger viewing angles of XRFs result in much smaller Doppler factors, δ, than those of GRBs. Relative to GRBs, XRFs have pulses that are much dimmer in fluence (which is proportional to δ^3) or in photon number-count (which is proportional to δ^2). Thus, only relatively close-by XRFs (i.e. XRFs with relatively small z) are detected with the current sensitivities of the X-ray instruments, on board HETE and Integral. Thus the optical AG of XRFs should contain a detectable contribution of an SN akin to SN 1998bw, displaced to the XRF's position and peaking about 20 days after the SN exploded and the XRF (Dar & De Rújula 2003; Dado et al. 2003f). Such a smoking-gun signature have already been observed in the AGs of XRF 030723 (Fynbo et al. 2003, 2004) and XRF 031203: Bersier et al 2004; Tagliaferri et al. 2004; Thomsen et al. 2004; Gal-Yam et al. 2004), and are shown in Fig. (13) and Fig. (14), respectively.

3. GRB/XRF-SNIa association?

Little is known for sure about the progenitors or the production mechanisms of Type Ia SNe. The prevailing theory is that accretion onto a C/O White Dwarf (WD) from a companion star in a close binary system causes their collapse —accompanied by a thermonuclear explosion— when the accreting WD's mass exceeds the Chandrasekhar limit (Whelan & Iben 1973). In the case of a WD–WD binary, the trigger may also be a merger, the end-result of a shrinking of the orbit due to gravitational-wave emission (Iben & Tutukov 1984; Webbink 1984).

In every one of the quoted scenarios, the specific angular momentum of the collapsing system is likely to be large. It is natural to expect that the collapsing object may have an axial symmetry leading to the bipolar ejection of jets of CBs, as in quasars, microquasars and the core-collapse SNe responsible —in the CB model— for long-duration GRBs. About

$70\% \pm 10\%$ of all SN explosions in the local Universe are of the core-collapse types, the rest being Type Ia SNe (Tamman, Loeffler & Schroder 1994; van den Bergh & McClure 1994). Intriguingly, $\sim 75\%$ of all GRBs are long and the rest are short. The coincidence may not be accidental. As discussed in detail in Dar & De Rújula (2003), the environment of Type-Ia SNe appear to be scaled-down versions of the corresponding properties of core-collapse SNe. The stage is naturally set to suspect that short GRBs may be a time-contracted —but otherwise very similar— version of the long GRBs.

The progenitors of core-collapse SNe are short-lived massive stars. Consequently, most of their explosions take place in star-formation regions, in superbubbles produced by the winds of massive stars and the ejecta from previous SNe. The ISM density in these bubbles is $n \sim 10^{-2}$–10^{-3} cm^{-3}. The progenitors of Type Ia SNe are long-lived and are not confined to star-formation regions. Their explosions take place in a normal ISM of typical density $n \sim 0.1$–1.0 cm^{-3}. For CBs with a baryon number 100 times smaller in short GRBs than in long ones (Dar & De Rújula 2003), and even for a density around a short GRB as low as $n = 10^{-2}$ cm^{-3}, the characteristic time of decline of the AGs of short GRBs is ~ 50 times shorter than for long ones. Moreover, the smaller CB's radius ($R_\infty^2 \sim [N_{CB}/n]^{2/3}$; Eq. (16) of Dado et al. 2002a) also reduces the intensity of the AGs considerably. When the CBs enter the ISM (within a couple of minutes of observer time), the combination of these effects makes the AGs of short GRBs much harder to detect than those of long ones. The only chance to detect the AG of short GRBs is at the very early time when the CBs plough through the short-range circumstellar wind. Indeed, very early X-ray AGs of short GRBs, declining rapidly with time, have actually been detected tens to hundreds of seconds after burst (e.g. Frederiks et al. 2003).

In long GRBs the AG is a "background" that made it difficult for the GRB community to consider the possibility that they are all associated with SNe, as they are in the CB model (in which this background is very well understood). One redeeming feature of the fact that the AGs of short GRBs decline so fast is that there will be no background to the detection of a potentially associated Type Ia SN. Moreover, the peak bolometric luminosity of SNe of type Ia, $L_{Ia} \approx 10^{43.35}$ erg s^{-1}, reached around $t \sim (1+z) \times 20$ days after burst (e.g. Leibundgut & Suntzeff 2003), is much larger than that of a core-collapse SNe. If these SNe were to be found in the directional error boxes of short GRBs, they could be used to localize them, to identify their host galaxies and their location within them, and to measure their redshifts. This may significantly increase the detection rate of Type Ia SNe at cosmological distances.

4. Concluding Remarks

The observational data on well localized long GRBs/XRFs clearly indicate that most, perhaps all, long duration GRBs/XRFs are produced in SN explosions akin to 1998bw. The view held by the majority of the GRB community, that GRB 980425 belongs to a rare class of dim GRB, is losing ground. Deviations from the "standard candle ansatz" for SNe associated with GRBs are expected and may already been observed (GRB 0212111: Della Valle et al. 2003; XRF 030723: Fynbo et al. 2004; XRF 030903: Cobb et al. 2004; GRB 020104: Levan et al. 2004 and GRB 020305: Gorosabel et al. 2004 in preparation) . But, it is premature to conclude how accurate the standard candle ansatz is. Observed deviations can be intrinsic, but they may also result from measurement errors, inaccurate knowledge of the contribution from the host galaxy at different wavelengths and inaccurate estimates of the intrinsic AG of the GRB at late time. Even if the deviations are genuine, they may partly result from different circumburst environments, from time dependent extinction along the line of sight in the host galaxy due to sublimation of dust by the GRB and AG, and due to contamination of the SN light by light echoes from the GRB and the very bright phase of the AG (perhaps also present in the template SN 1998bw).

So far, the observational data on the GRB/XRF-SN association have revealed only the tip of an iceberg. In fact, little is known about the GRB-SN association: We do not know yet whether only a subclass of Type Ib/c SN explosions (hypernovae: Iwamoto et al. 1998; Woosley 1999) produce GRBs or whether all SNe of Type Ib/c, or perhaps SNe of Type II as well (Dar & Plaga 1999; Dar & De Rujula 2000), produce GRBs/XRFs. We do not know whether short duration GRBs/XRFs are also associated with SN explosions, in particular with SNe Type Ia (Dar & De Rújula 2003). We do not know whether the progenitors of long GRBs/XRFs are single stars or binary stars. We do not know: what are the compact remnants of long GRBs/XRFs – neutron stars? strange-quark stars? or stellar black holes? We also do not know whether these compact remnants are very active for a considerable time after birth, e.g., as soft gamma ray repeaters, anomalous X-ray pulsars or microquasars (if the progenitor star was in a close binary). Or do they cool quickly into a relatively quiet remnant?

As in quasars and in microquasars, the production mechanism of highly relativistic and narrowly collimated jets in SN explosions is unknown. Nor do we know the exact mechanism which explodes SNe. We even do not known whether the GRBs are produced promptly in the SN explosions, as advocated by the collapsar model of GRBs (Woosley et al. 1999), or whether they are produced in a second bang driven by fall-back material onto a protoneutron star and/or loss of its rotational and thermal support within hours after core collapse (De

Rújula 1987) as advocated by the cannonball model of GRBs (Dar & De Rujula 2000,2003)[6].

Finding the correct answers to these questions will require enormous efforts, both observational and theoretical, which, no doubt, will take a long time and will require a lot of ingenuity and good luck. But some answers are bound to be provided soon. It is hoped that a large sky coverage and a fast localization on board of the prompt γ-ray emission with advanced γ-ray telescopes such as SWIFT, and that a rapid multiwave follow up in the afterglow phase that continues with a high precision until late times, will provide some of the answers. Some answers may also come from gravitational wave detectors like LIGO, high energy γ-ray telescopes like GLAST and high energy neutrino telescopes such as ICE-CUBE and ANTARES. The Hubble and Spitzer space telescopes together with the present and future armada of very large ground based telescopes may provide reliable light curves and perhaps spectra of SNe in AGs of GRBs with $z > 1$. But irrespective of these, the GRB/XRF-SN association with star formation may provide a powerful tool for studying the history of star formation in the universe and the expansion rate of the universe – if GRBs are produced by nearly 'standard candle' SNe as indicated by the cannonball-model analysis of the afterglows of GRBs with known redshift.

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[6]The observational data on the GRB-SN association does not seem to support the supranova model (Vietri and Stella 1998) where GRBs are produced months or years after a core collapse SN explosion by a delayed collapse of the neutron star to a strange-quark star or a black hole due to loss of rotational and thermal support (e.g., Dar 1999b), the supranova model is not ruled out as a mechanism for short duration GRBs.

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Table 1. Photometric (P) and spectroscopic (S) evidence for SN light in GRBs/XRFs with known redshift

GRB/XRF	z	SN	E_{iso}[erg]	evidence
980425	0.0085	Y	7.8×10^{47}	P+S
031203	0.1055	Y	3.0×10^{49}	P
030329	0.1685	Y	1.1×10^{52}	P+S
020903	0.251	?	1.1×10^{49}	P
011121	0.360	Y	4.6×10^{52}	P
990712	0.433	Y	5.3×10^{52}	P
010921	0.451	Y	1.4×10^{52}	P
020405	0.69	Y	7.2×10^{52}	P
970228	0.695	Y	1.1×10^{52}	P
991208	0.706	Y	1.5×10^{53}	P
970508	0.835	?	1.0×10^{52}	P
000210	0.846	?	1.7×10^{53}	P
980703	0.966	?	2.3×10^{53}	P
021211	1.006	Y	6.0×10^{51}	P+S
991216	1.020	?	5.4×10^{52}	P
000911	1.058	Y	4.0×10^{53}	P
980613	1.097	?	5.4×10^{51}	P
000418	1.118	?	2.6×10^{53}	P
020813	1.225	N	7.8×10^{53}	
010222	1.477	N	8.6×10^{53}	
990123	1.600	N	2.0×10^{54}	
990510	1.619	N	5.0×10^{53}	
030226	1.989	N	6.5×10^{52}	
000301c	2.040	N	4.6×10^{52}	
000926	2.037	N	2.6×10^{53}	
011211	2.141	N	6.7×10^{53}	
021004	2.330	N	5.6×10^{52}	
971214	3.418	N	2.1×10^{53}	
000131	4.500	N	1.2×10^{54}	

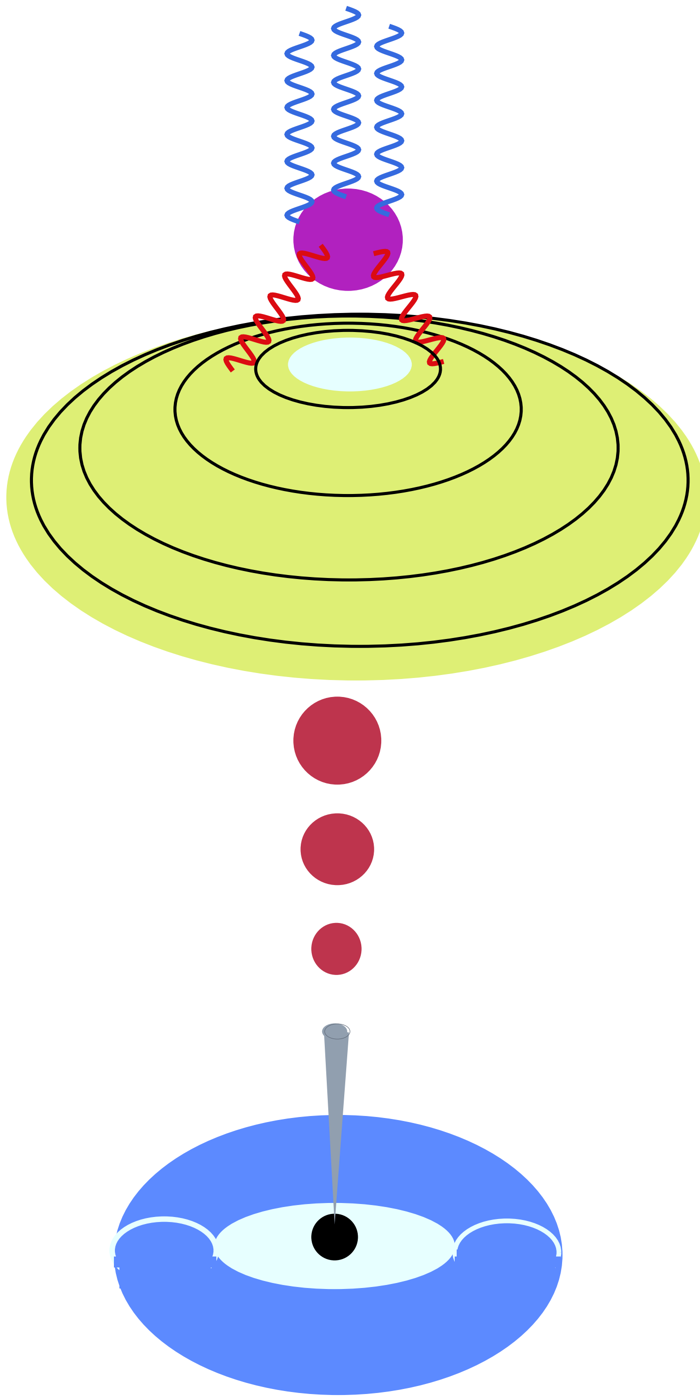


Fig. 1.— An "artist's view" (not to scale) of the CB model of GRBs and their afterglows. A core-collapse SN results in a compact object and a fast-rotating torus of non-ejected fallen-back material. Matter (not shown) abruptly accreted onto the central object produces a narrowly collimated jet of CBs, of which only some of the "northern" ones are depicted. As these CBs move through the "ambient light" surrounding the star, they Compton up-scatter its photons to GRB energies.

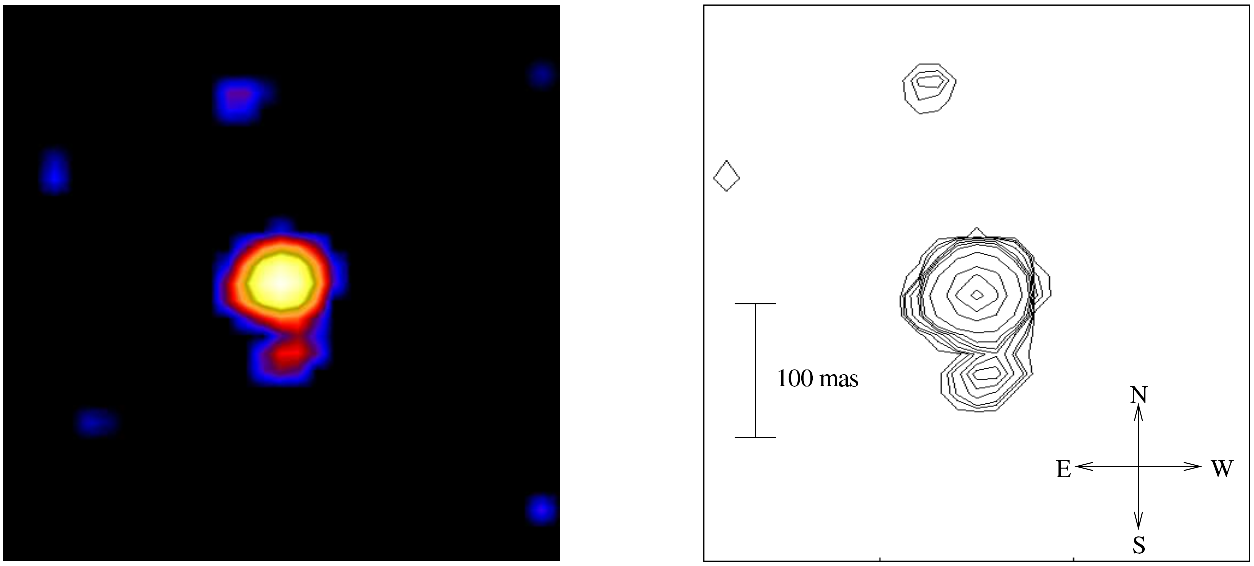
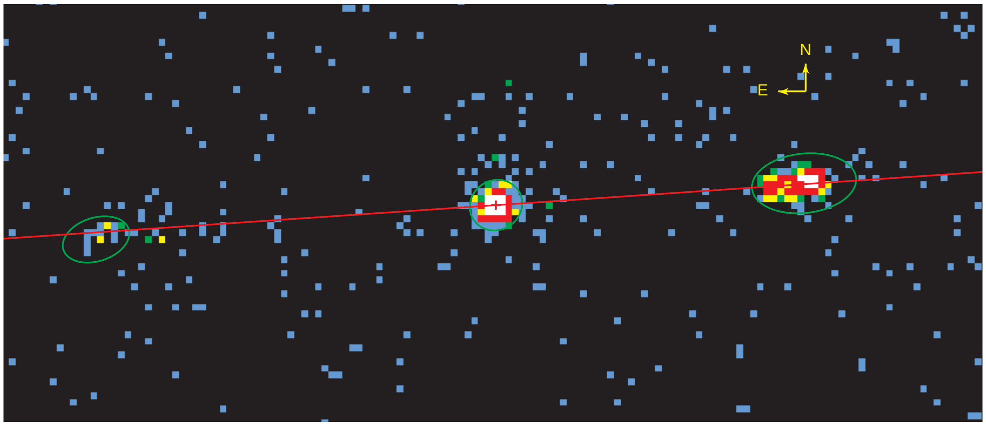


Fig. 2.— The two mystery spots emitted by SN 1987A in opposite axial directions (Nisenson & Papaliolios 2000). The northern and southern bright spots are compatible with being CBs emitted around the time of the SN explosion and travelling at a velocity equal, within errors, to c. One of the *apparent* velocities is superluminal. The corresponding GRBs were not pointing in our direction.



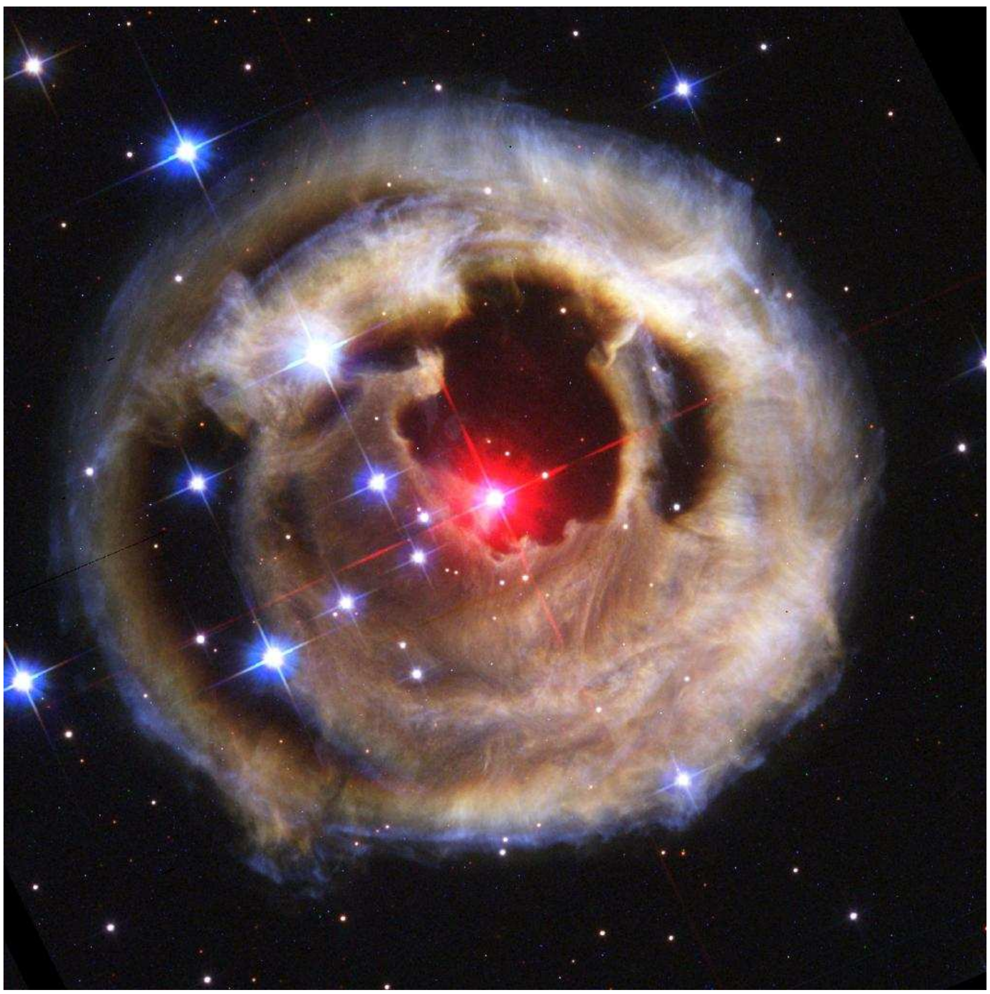


Fig. 3.— Upper panel: Two relativistic CBs emitted in opposite directions by the microquasar XTE J1550-564, seen in X-rays by Corbel et al. 2002. Lower panel: HST picture from 28 October 2002 of the *glory*, or light echo, of the stellar outburst of the red supergiant V3838 Monocerosis in early January 2002. The light echo was formed by scattering off dust shells from previous ejections (Bond et al. 2003).

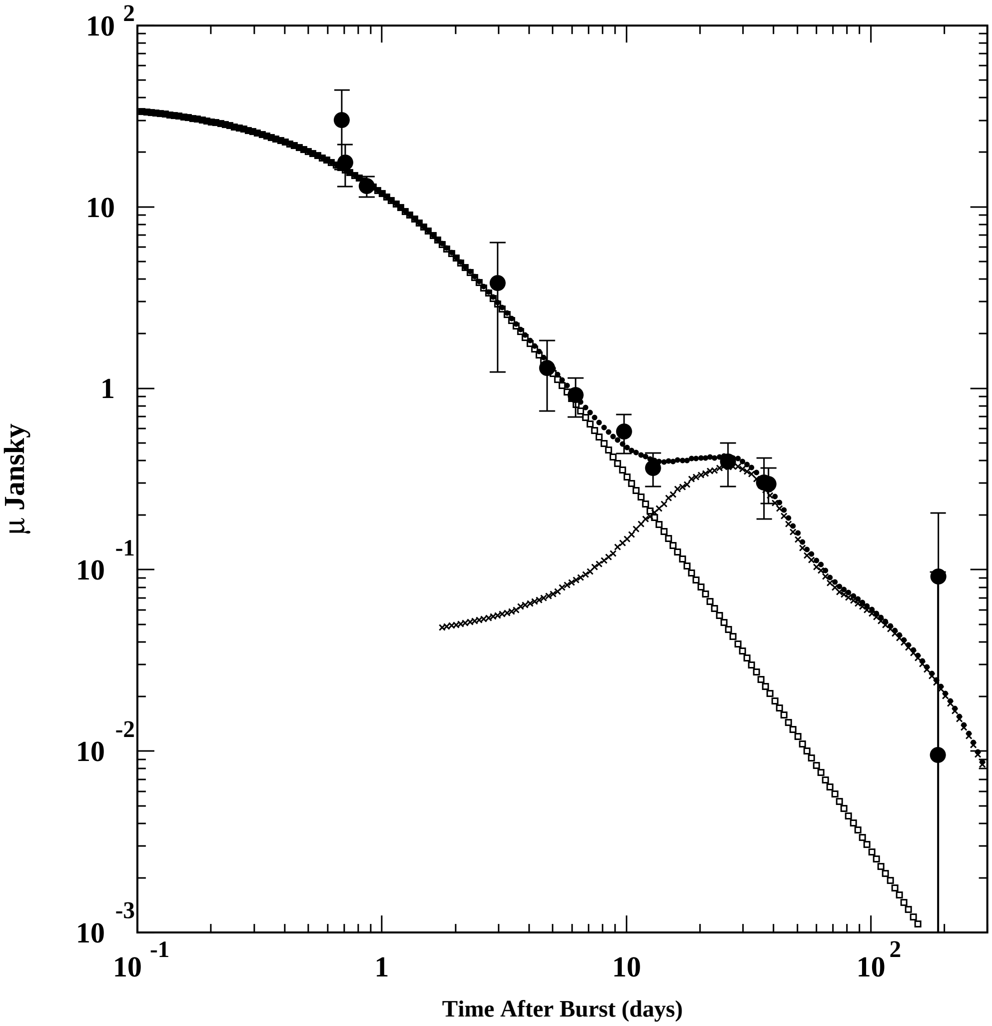


Fig. 4.— The CB model fit (Dado et al. 2002a) for the R-band AG of GR 970228 [$z = 0.695$], after subtraction of the contribution from the host galaxy. The contribution from a 1998bw-like supernova placed at the GRB's redshift and corrected for extinction, is indicated by a line of crosses. The SN bump is clearly discernible.

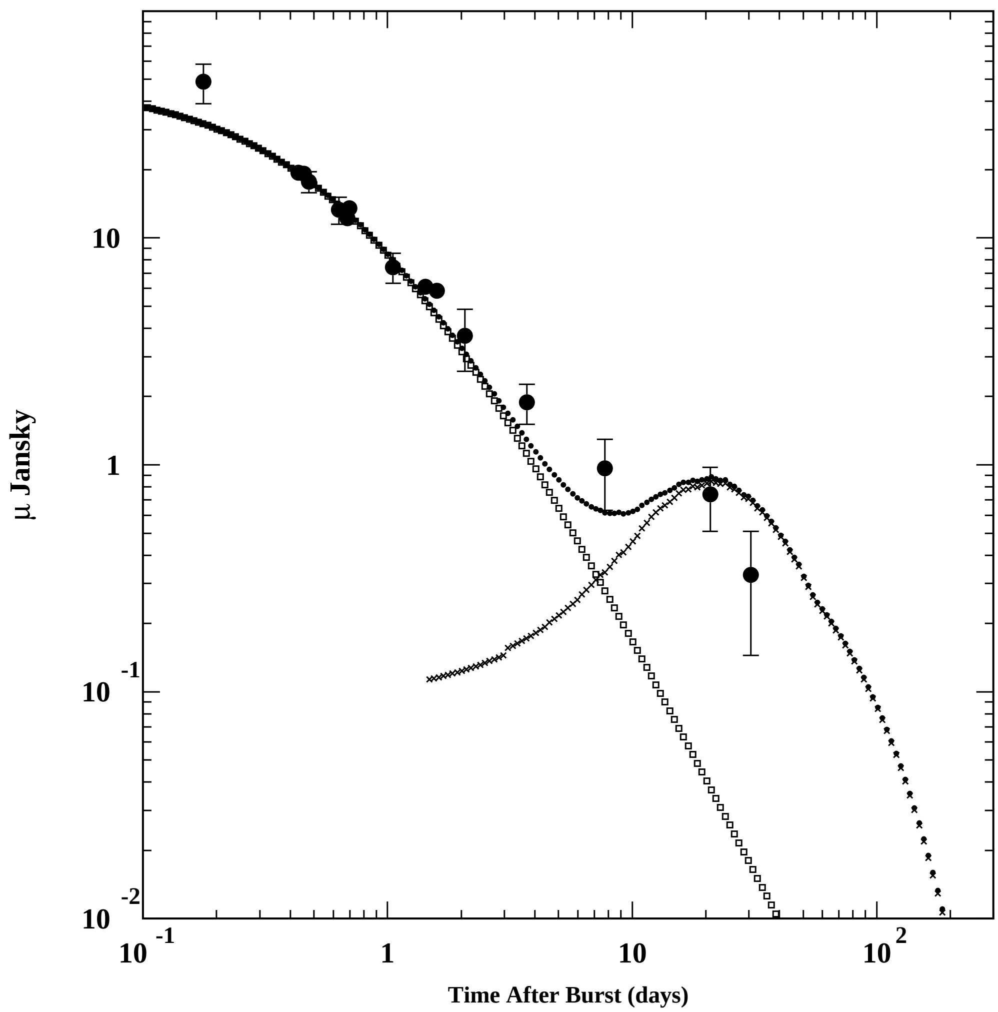


Fig. 5.— CB model fit (Dado et al. 2002a) to the R band AG of GRB 990712 [$z = 0.433$] after subtraction of the contribution from the host galaxy. The theoretical contribution from an SN 1998bw-like supernova was dimmed by the known extinction in the Galaxy and our estimated extinction in the host from the early time AG. The SN is clearly discernible, but a bump at slightly earlier times than that of a standard-candle SN 1998bw would provide a better description.

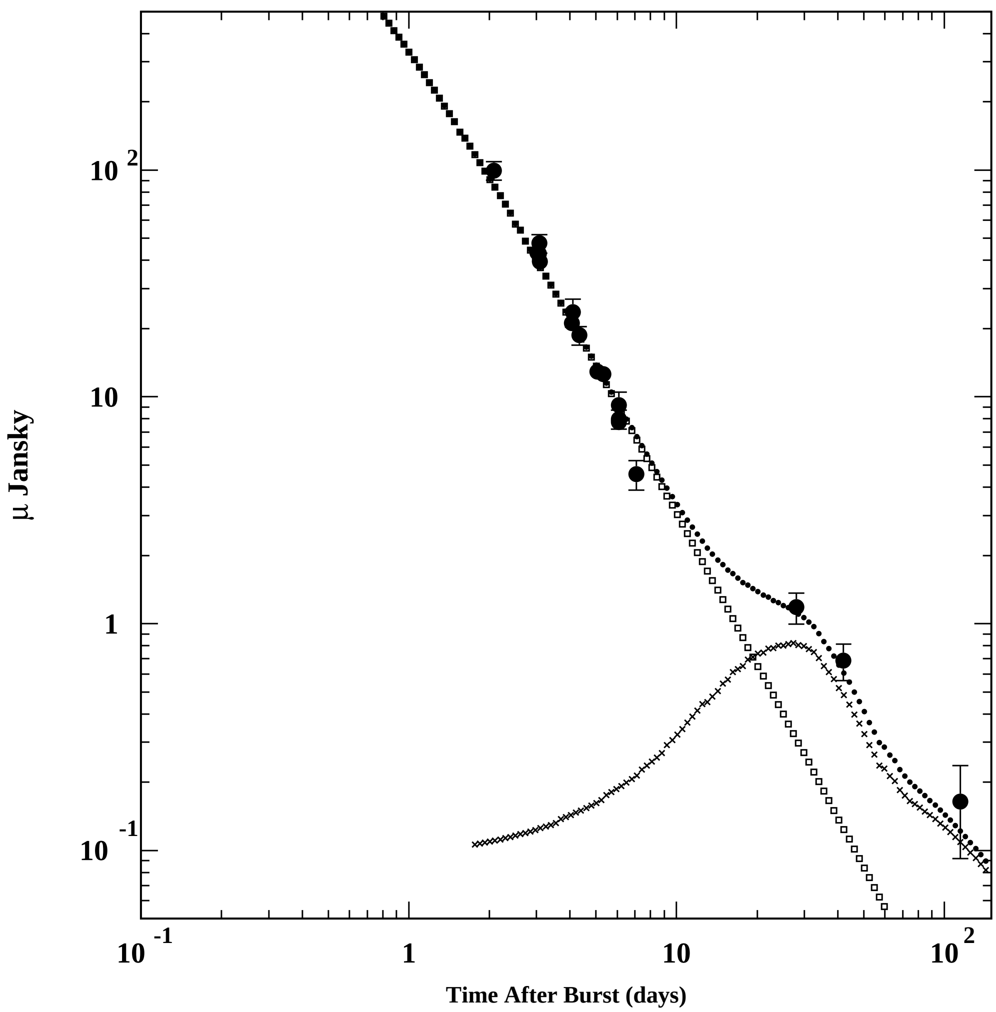


Fig. 6.— The CB model fit (Dado et al. 2002a) for the R-band afterglow of GRB 991208 [z = 0.706], after subtraction of the host galaxy's contribution. The contribution from a 1998bw-like supernova placed at the GRB's redshift, corrected for extinction, is indicated by a line of crosses. The SN contribution is clearly discernible.

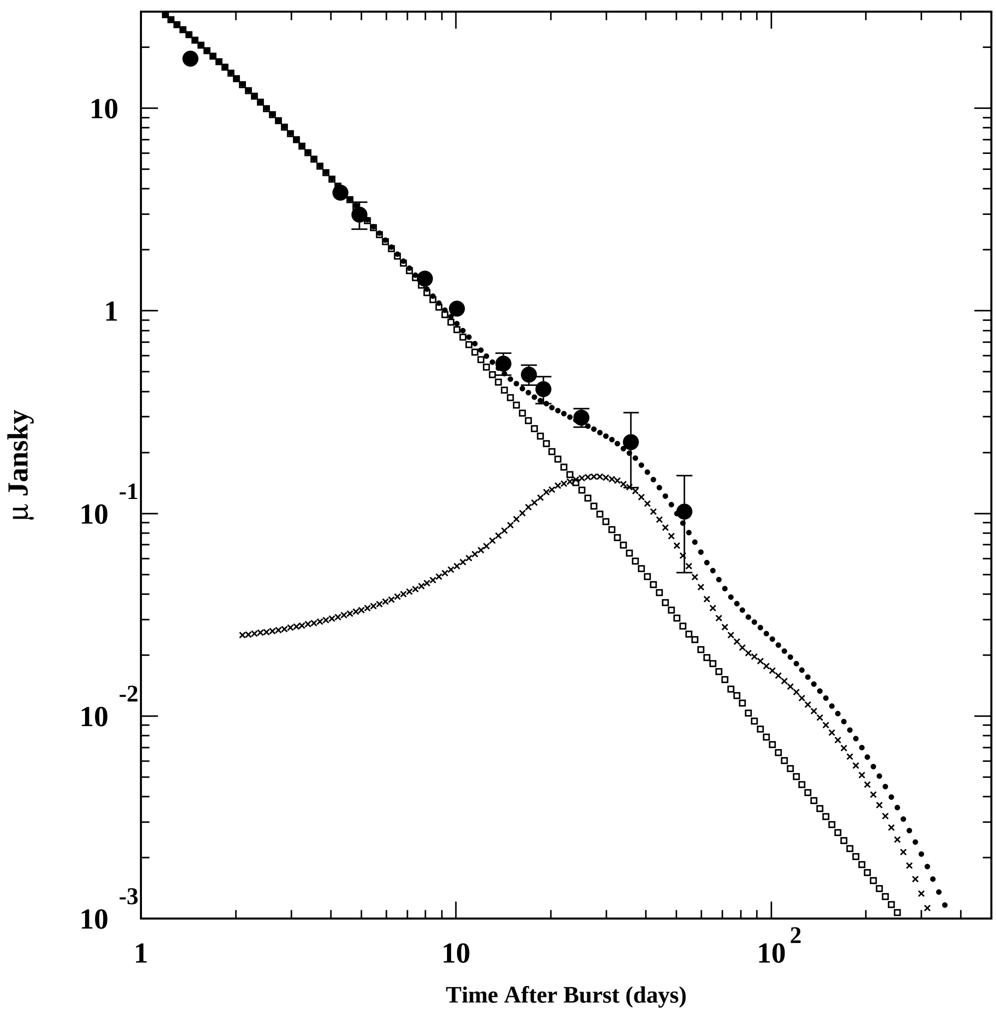


Fig. 7.— The CB model fit for the R-band afterglow of GRB 000911 [z = 1.006], after subtraction of the host galaxy's contribution. The contribution from a 1998bw-like supernova placed at the GRB's redshift, corrected for extinction, is indicated by a line of crosses. The SN contribution is clearly discernible.

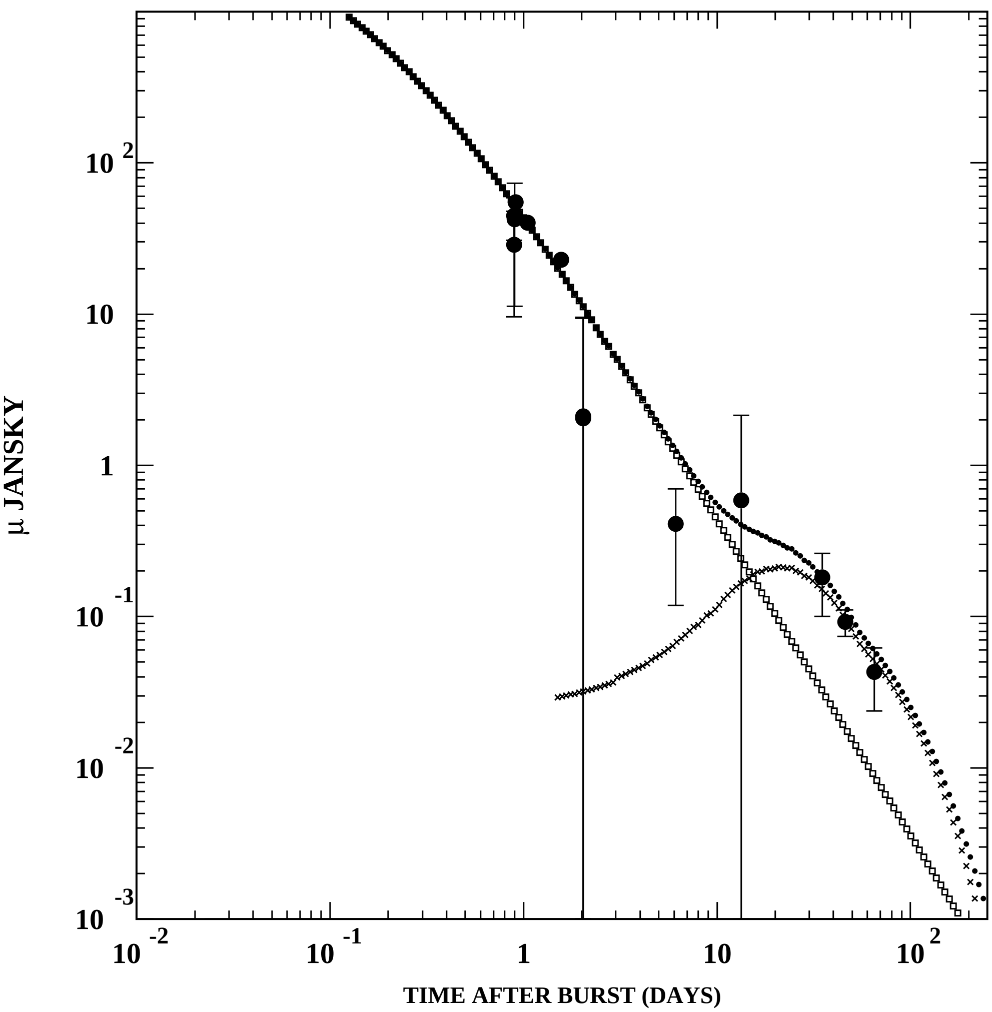


Fig. 8.— The CB model fit for the R-band afterglow of GRB 010921, [z = 0.451] after subtraction of the host galaxy's contribution. The contribution from a 1998bw-like supernova placed at the GRB's redshift, corrected for extinction, is indicated by a line of crosses. The SN contribution is clearly discernible.

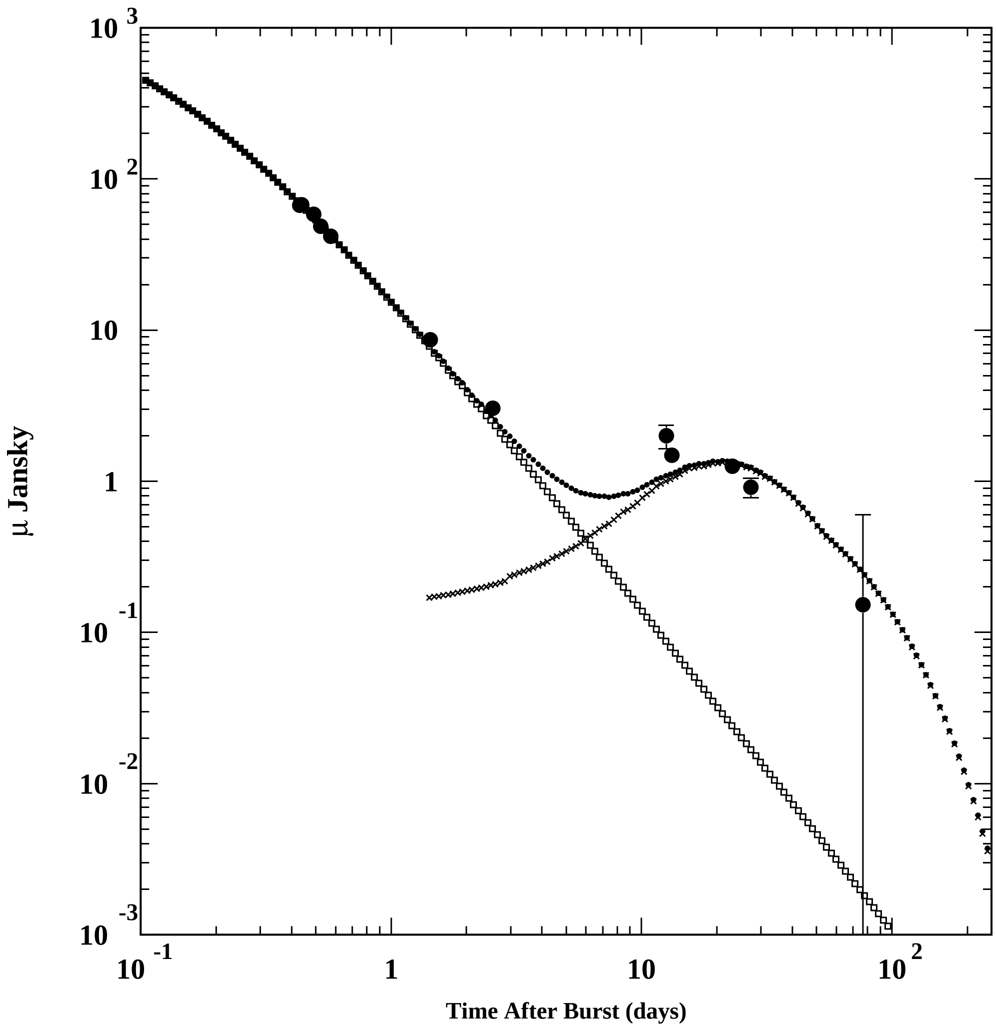


Fig. 9.— CB model fit (Dado et al. 2002b) for the R-band afterglow of GRB 011121 [$z = 0.36$] after subtraction of the contribution of the host galaxy. The contribution from a 1998bw-like supernova placed at the GRB's redshift, indicated by a line of crosses, is corrected by estimated extinction factor. The SN contribution is clearly discernible.

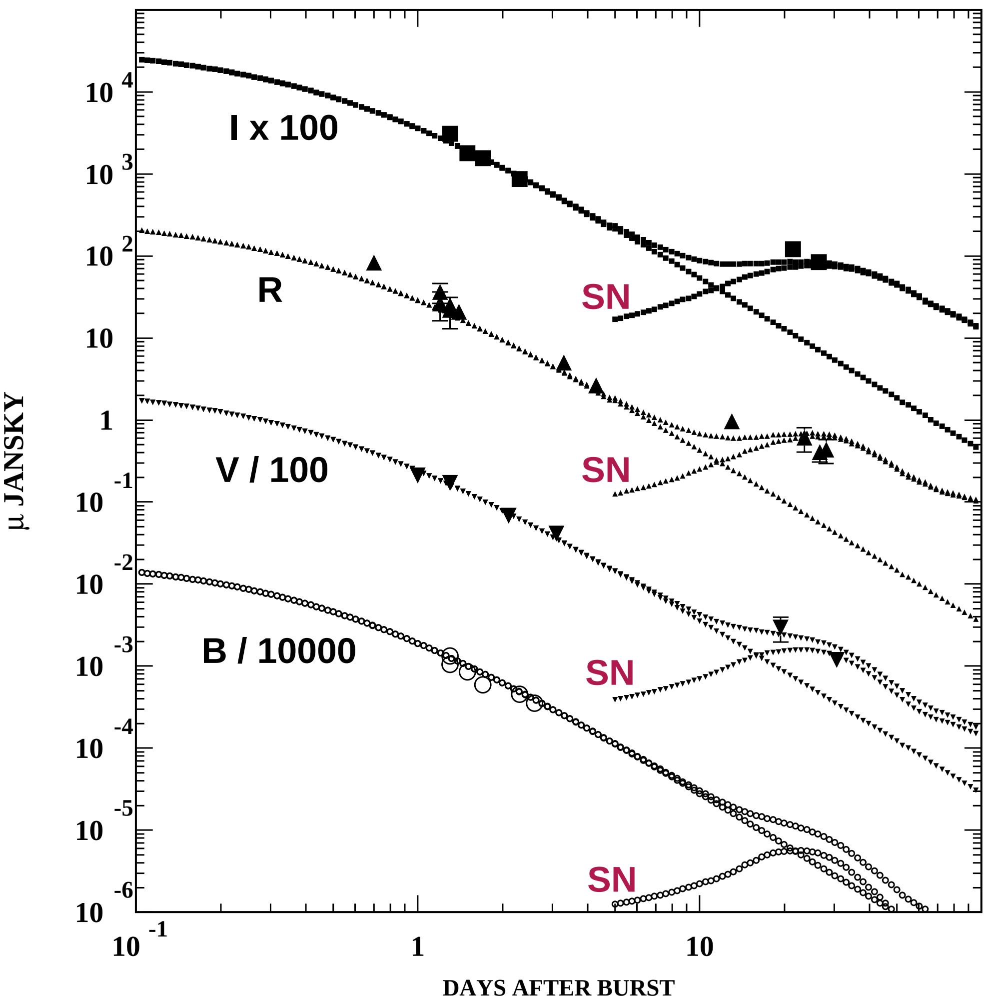


Fig. 10.— CB model fit (Dado et al. 2002c) to the measured I, R, V, and B-band AG of GRB 020405 [z = 0.69], multiplied by 100, 1, 1/100, 1/10000, respectively with the the host galaxy contribution subtracted. The theoretical contribution from an SN 1998bw-like supernova was dimmed by the known extinction in the Galaxy and our estimated extinction in the host galaxy from the early-time AG.

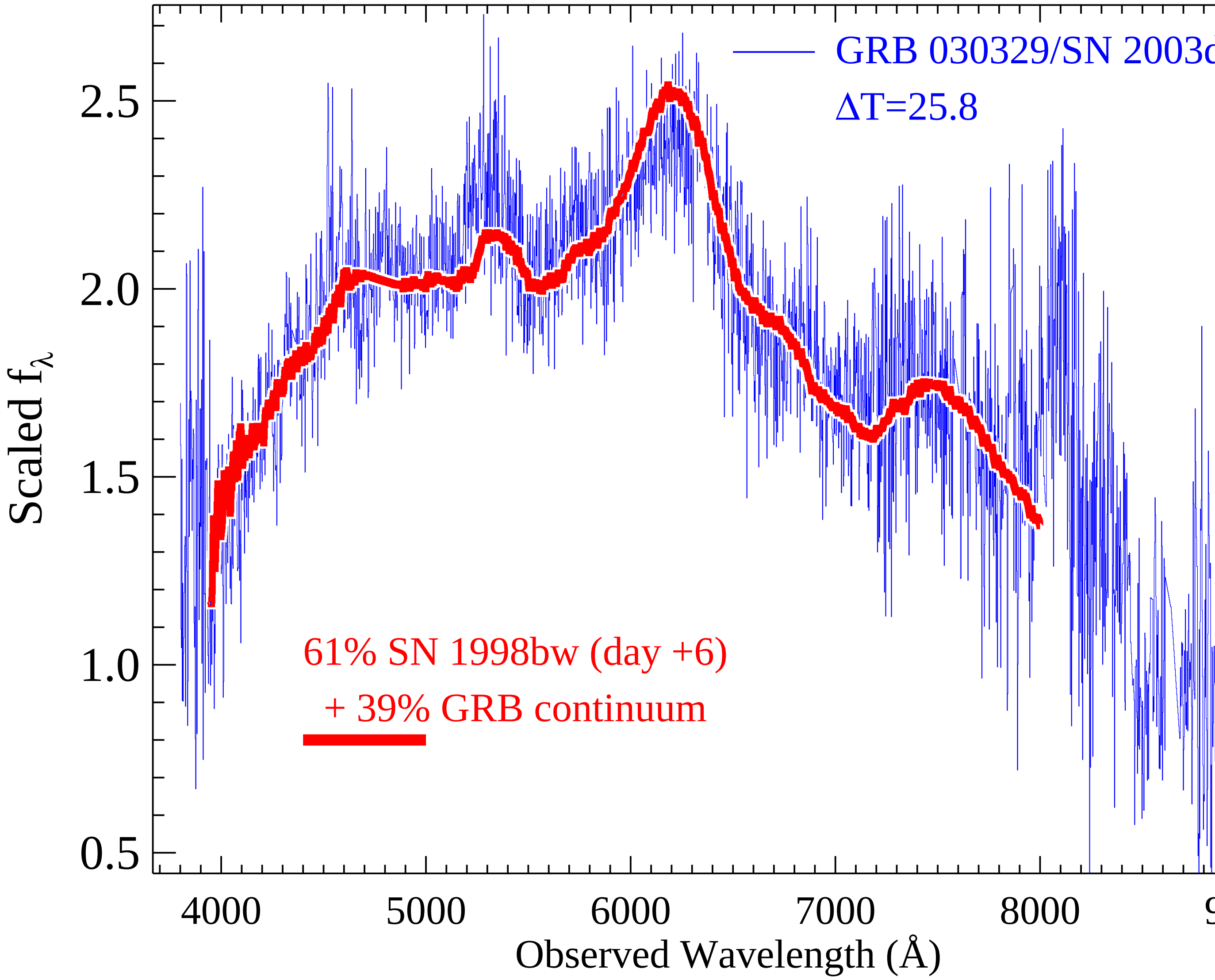


Fig. 11.— Observed spectrum (thin line) of the GRB 030329/SN 2003dh [$z = 0.1685$] afterglow at t=25.8 days after burst. The model spectrum (thick line) consists of 39% continuum and 61% SN 1998bw from 6 days after maximum. The figure is borrowed from Matheson et al. 2003

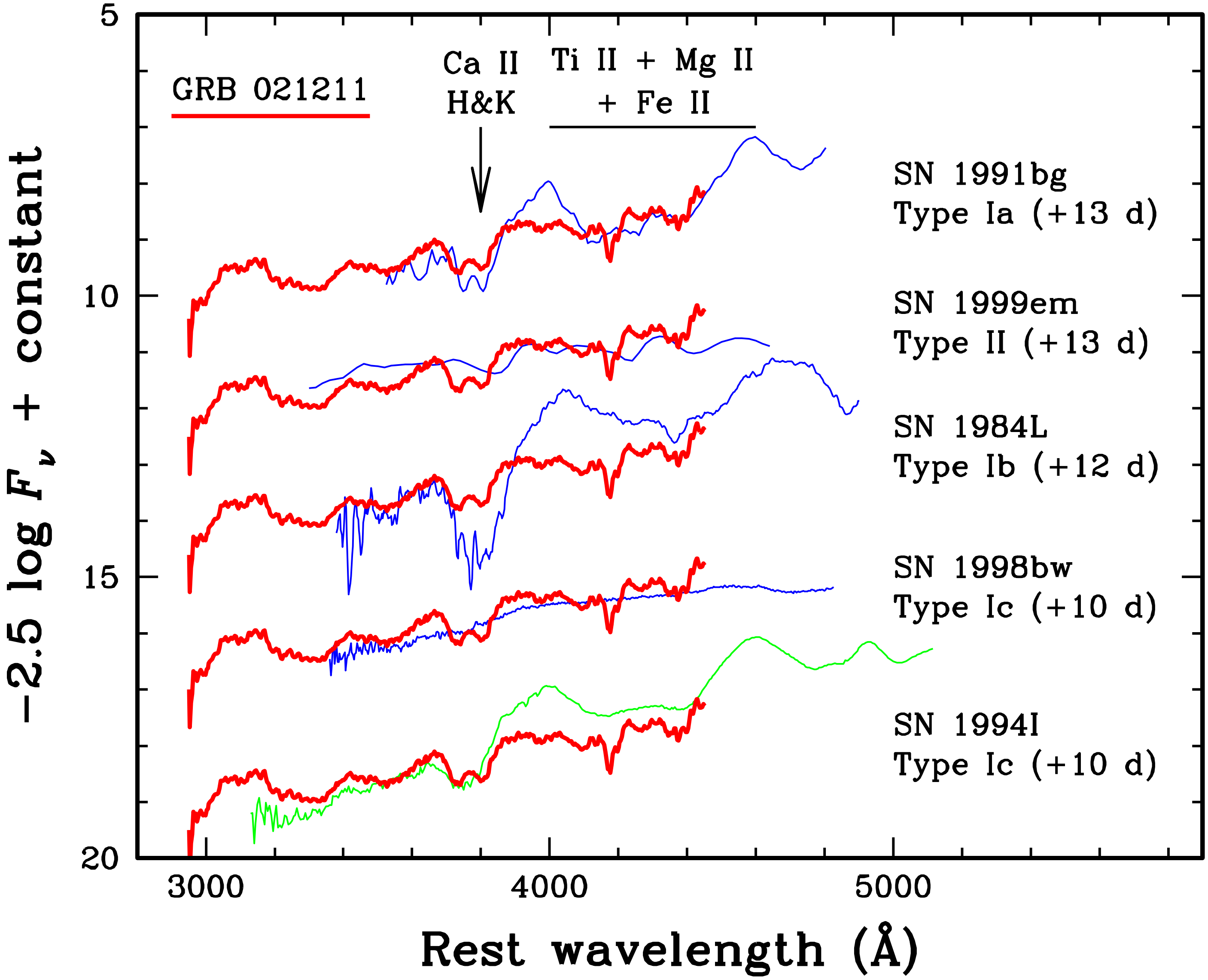


Fig. 12.— Rest-frame spectrum of the afterglow of GRB 021211 [$z = 1.006$] 27 days after the GRB (thick lines), compared with that of several SNe (thin lines). The figure was borrowed from Dela Valle et al. 2003

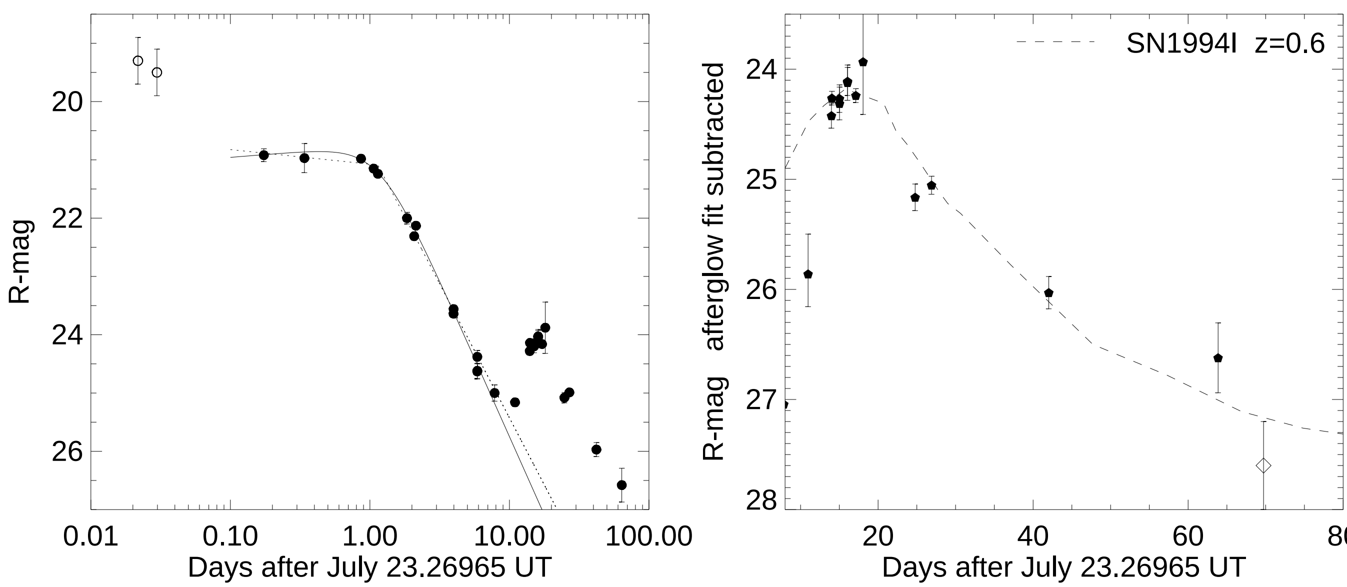


Fig. 13.— Left: The R-band light curve of the afterglow of XRF 030723 borrowed from Fynbo et al. 2004. The dashed and solid lines are broken power-law fits to the data points. Right: The late time R-band light curve after subtraction of the power-law fit. The dashed curve shows the B-band light curve of the type Ic SN 1994I redshifted to $z = 0.6$ by Fynbo et al. (2004) and scaled up in flux by one magnitude.

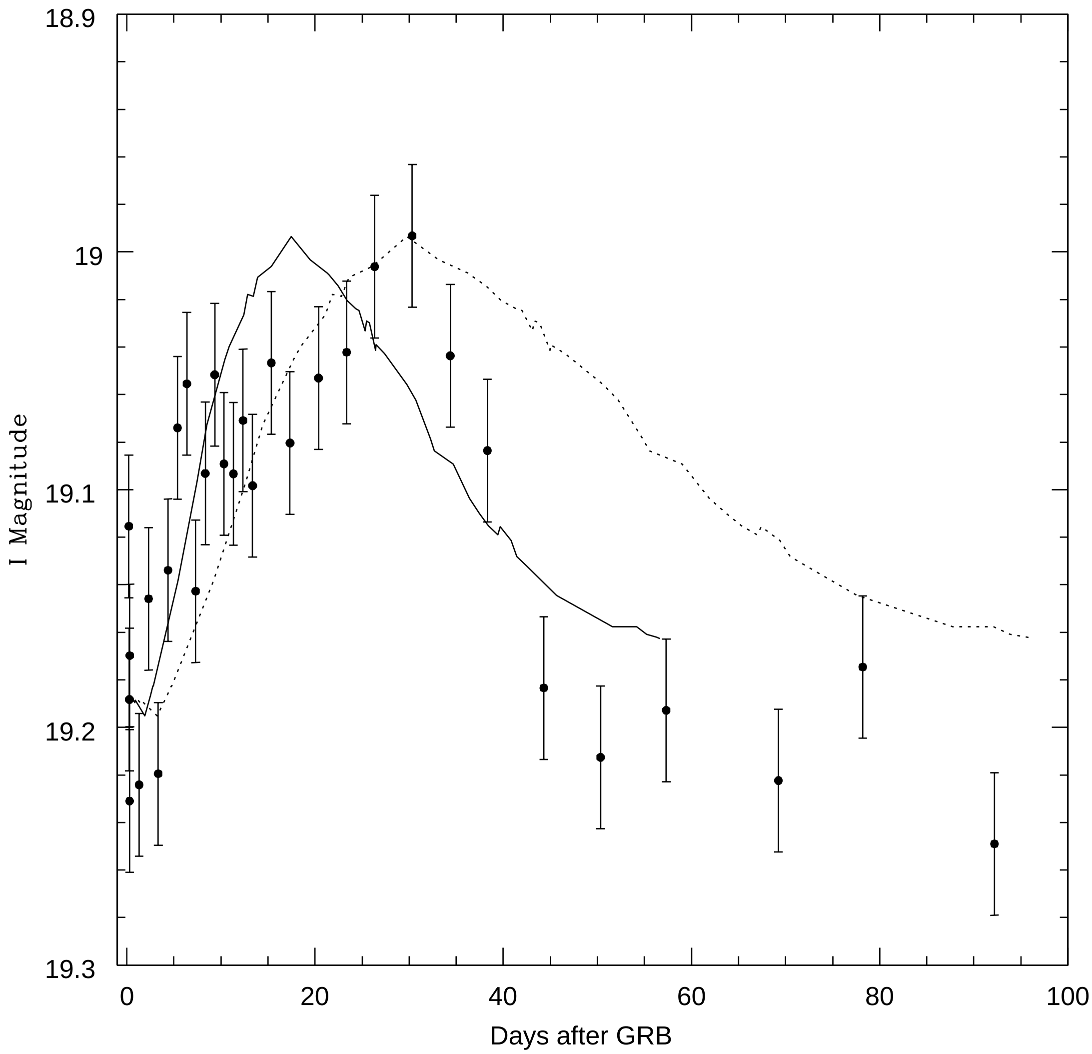


Fig. 14.— The I band lightcurve of the AG of XRF 030903 [$z = 0.1055$], obtained by Cobb et al. 2004 by subtracting the host galaxy contribution. The solid line is a template SN 1998bw that was displaced to the GRB position in the host galaxy. An additional 0.02 mag has been added to the shifted SN 1998bw lightcurve so that the SNe reaches the same peak brightness. If a stretch of 1.7 is applied (dotted line) the peaks coincide but the declines is inconsistent with the data.